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Acta Astronautica 58 (2005) 168 – 174

ACTA ASTRONAUTICA

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Space debris mitigation measures in India

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Received 20 June 2005; received in revised form 31 August 2005; accepted 13 September 2005

Abstract

The Indian Space Research Organization (ISRO) recognizes the importance of the current space debris scenario, and the impact it has on the effective utilization of space technology for the improvement in the quality of life on the Earth. ISRO is committed to effective management of the threats due to space debris. Towards this commitment ISRO works on different aspects of space debris, including the debris mitigation measures. This paper highlights the activities and achievements in the implementation of the mitigation measures. ISRO successfully designed and developed a propellant venting system for implementation in the existing upper stage of India's Polar Satellite Launch Vehicle (PSLV), which uses Earth-storable liquid propellants. GSLV also employs passivation of the Cryogenic Upper Stage at the end of its useful mission. ISRO's communication satellites in GSO are designed with adequate propellant margins for re-orbiting at the end of their useful life to a higher graveyard orbit. A typical successful operation in connection with INSAT-2C is described. ISRO developed its debris environmental models and software to predict the close approach of any of the debris to the functional satellites. The software are regularly used for the debris risk management of the orbiting spacecraft and launch vehicles. ISRO recognizes the role of international cooperation in the debris mitigation measures and actively contributes to the efforts of the Inter-Agency Space Debris Coordination Committee (IADC) and United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

1. Introduction

The prime objective of the Indian Space Research Organization (ISRO) has been to develop space technology and its application to various national tasks. Since 1969, when it was set up, ISRO has established space systems like the INSAT for telecommunication, television broadcasting and meteorological services, and the Indian Remote Sensing Satellites (IRS) for resources monitoring and management. ISRO has developed the satellite launch vehicles PSLV and GSLV to place these satellites in the required orbits.

The primary aim of ISRO's programme is to promote development and application of space science and technology to assist in all-round development of the nation. In the 1980s, ISRO initiated a major revolution in India's communication sector. The Indian national satellite (INSAT) System is one of the largest in the Asia-Pacific region today. The INSAT System provides services in S-band, C-band, Extended C-band and Ku-band. It also provides meteorological images through very high resolution Radiometer and CCD cameras. INSAT system serves many other important sectors of the Indian economy.

Today, India has also the largest constellation of Remote Sensing Satellites (IRS), which is providing

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0094-5765/$ - see front matter
doi:10.1016/j.actaastro.2005.09.002

services both at the national and global levels. Great emphasis is placed on the operational use of remote sensing applications in the fields of water resources, agriculture, soil and land degradation, mineral and groundwater exploration, geomorphological mapping, coastal and ocean resources monitoring, environment, ecology and forest mapping, land-use and land-cover mapping.

Unfortunately, over a period of time, international space initiatives have left behind a plethora of space objects that no longer serve any useful functions, but pose risk to space operations. Thus, space debris becomes an important subject for all space faring nations in particular and humanity in general. This paper describes the milestones in the space debris mitigation measures in India.

2. Over view of space debris activities in ISRO

The space debris activities in ISRO have been addressed in the design and operational phases of its launch vehicle and satellite programs. In the design of PSLV final stage, which uses earth-storable liquid propellants, a propellant venting system has been designed. ISRO's launch vehicle, GSLV, also employs passivation of the Cryogenic Upper Stage at the end of its useful mission. The ISRO's communication satellites in Geo-synchronous orbit (GSO) are designed with adequate propellant margins for re-orbiting to a higher orbit at the end of their useful life. The strategy is implemented on a case-by-case basis consistent with national service requirements. The propulsion systems, by design, are built as integrated systems with the spacecraft bus and payload. The propulsion system is not separated in orbit. Also these are liquid propulsion systems and the ejecta do not contain any solid particles.

In the operational phase, the last stage of PSLV has been passivated beginning with PSLV-C4, which was successfully launched on 12th September 2002. The options considered for implementation of passivation are presented in the paper. The pressure measurements during the flight were telemetered indicating the successful implementation of passivation of the stage. With the implementation of this passivation, the possibility of on-orbit fragmentation has been minimized in all the future flights of PSLV. India's launch vehicles, PSLV and GSLV, and the satellites IRS, INSAT and GSAT series are designed in such a way that no operational debris is created in the launch and deployment phases of the mission.

At the end of mission, the GEO satellites are planned to be re-orbited in accordance with the IADC guidelines. Also, the batteries are safed in order to prevent an orbit explosion. An example of the recently concluded GSO satellite re-orbiting is presented in this paper [1].

The analysis of close approaches of space debris with active ISRO spacecraft is carried out on a routine basis at the operational centers. ISRO developed the models and software to predict the close approach of any of the debris to the functional satellites [2]. The software are being regularly used during the control and management of the orbiting spacecraft, and are specially useful during the relocation of the geo-stationary satellites from one orbital slot to another orbital slot. The analysis software can also be used for planning the launch window. The planned lift-off time of PSLV-C4 launch vehicle in September 2002 was modified by a few minutes to avoid possible close approach by some of the existing space debris.

In the area of analytical modeling related to fragmentation, a number of approaches are developed to study the evolution of break up fragments [3–11]. Further modeling of fragmentation and subsequent decay of space objects in LEO and Geostationary Transfer orbit (GTO) are in progress [12,13]. In the area of protection, hypervelocity impacts are studied using finite element techniques [14].

As a member of the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS), and through ISRO's membership in the Inter-Agency Space Debris Coordination Committee (IADC), India is contributing significantly to the international efforts and activities in the field of space debris. This commitment is amply reflected in its hosting the 21st IADC Meeting in Bangalore during March 2003.

3. Passivation of upper stages

On-orbit explosions of spacecraft and upper stages create a substantial portion of the space debris. More than 40% of the catalogued space debris originated from such explosions. These breakups are caused by a wide variety of causes: battery failure, over-pressurization and/or ignition of fuels, accidental collisions, deliberate detonation, etc. About 170 cases of on-orbit fragmentations are reported so far; most of them due to propulsion related explosions. Glimpses of some major breakup events are given in Table 1.

Analyses of accidental fragmentation for both spacecraft and upper stages have shown that vehicle passivation, i.e. removal of all forms of stored energy, would

Table 1
Glimpses of some major breakup events

Object	Event year	Tracked pieces
OV2-1/LCS R/B	1965	470
NIMBUS 4 R/B	1970	372
COSMOS 1275	1981	306
SPOT1/Viking R/B	1986	489
STEP II R/B	1996	704
PSLV-C3 R/B	2001	330

eliminate most such events. Effective measures include the expulsion of residual propellants by burning or venting, the discharge of batteries, the release of pressurized fluids, safing of unused destruct devices, etc. Though studies on passivation of upper stage were initiated much earlier, the break up of PSLV-C3 R/B has accelerated the implementation of passivation scheme in the upper stage of PSLV from C4 mission onwards.

Passivation of the upper stage is successfully implemented in the stage design to avoid any explosions after its useful purpose is completed.

The following options were considered for passivation of PS4:

(1) Venting the trapped propellants and subsequently the pressurant through the main engines in a sequential manner by opening the main engine valves.
(2) Consuming the total propellants by restarting the main engines.
(3) Consuming the propellants by firing the reaction control thrusters meant for attitude stabilization.
(4) Venting the propellants through an additional branching in the feed lines of each propellant using separate pyrovalves added in the circuit.
(5) Venting the pressurant gas from the propellant tank and gas bottles along with the propellant vapors in the tanks through an additional branching in the pressurization lines of each tank using separate pyrovalves added in the circuit.

The last option considered was selected for the passivation of PS4 stage due to its simplicity and safety to the separated spacecraft.

In course of the design of the passivation system the following specific problem areas were addressed to and required corrective measures were incorporated in the design:

(1) Buckling of tank common bulkhead during passivation. MON-3 compartment is vented first to have a positive pressure in MMH tank.

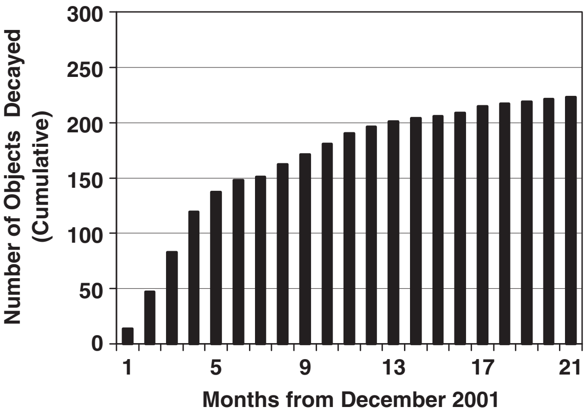

Fig. 1. Cumulative decay of PSLV-C3 debris fragments.

(2) To avoid exhaust plume interaction with the structure, location of the vent nozzles was selected to eliminate the interaction zone between the exhaust plume and the structure.
(3) To avoid contamination of the spacecraft, sufficient time gap is given before initiating passivation after spacecraft separation.
(4) Propellant freezing during passivation. Experiments with MON-3 gas in high altitude test facility indicate no freezing of propellants. Thermal analysis also corroborates this.

Pressure measurements telemetered during the flight of PSLV-C4 substantiated the successful implementation of the passivation scheme. ISRO's launch vehicle, GSLV, also employs passivation of the cryogenic upper stage at the end of useful mission.

A detailed analysis was made on the fragmentation of the PSLV-C3 Upper Stage, which took place before the implementation of passivation. The prefragmentation orbit of the rocket body was 550 km × 675 km, with an inclination of 97.9°. About 330 catalogued fragments were generated in this explosion. Even though a large number of fragments were generated in this event, the objects soon decayed. By September 2003 about 70% of the fragments have decayed. A pictorial representation of the decay during the first 12 months is shown in Fig. 1. Different deterministic and stochastic models, developed in ISRO, for fragmentation events, are reported in [3–11].

4. End-of-mission re-orbiting from GSO

ISRO's communication satellites in GSO are designed with margins for re-orbiting to a higher orbit at

the end of their useful life. The strategy is implemented on a case-by-case basis consistent with National service requirements. The re-orbiting and decommissioning operation of INSAT-2C are briefly described here. The operations are planned and executed by the Master Control Facility at Hassan [1].

INSAT-2C was launched on December 6, 1995 and had been collocated with INSAT-2B at 93.5° until March 01, 2002. The spacecraft was repositioned to 48°E longitude successfully on April 05, 2002 for operational reasons. Subsequently, INSAT-2C had fulfilled all its mission goals and a decision was taken for decommissioning INSAT-2C.

The decommissioning of INSAT-2C was planned along the lines of International Guidelines of Space Debris management by targeting apogee and perigee heights above GSO. The maneuvers had to be planned and executed having observed the propellant-depleted condition. The micro-pulsing maneuver operations were started on June 10, 2003 and continued until July 25, 2003 to obtain a drift rate of 1.71°/rev westward drift rate. In this process, orbital perigee height was increased to 127 km above GSO and Apogee height was increased to 150 km above GSO.

As per the IADC guidelines, at the end of useful mission life, spacecraft should be disposed off to the graveyard orbit with minimum perigee height above GSO given by

$$\text{Perigee height (km)} \geqslant 235 + 1000 \times \text{reflectivity coefficient} \times (\text{area}/\text{mass}).$$

For the case of INSAT-2C, the above requirement translates to 281.4 km above GSO.

The initial Perigee height was 30 km below GSO and Apogee height was 30 km above GSO. It was decided to raise the perigee first to reach the level of observed apogee height and further maneuvers to alternate between perigee and apogee rising suitably. Increasing the orbital height results in a westward drift. Necessary operational procedures were worked out to effect the delta-velocity change to the orbit. In particular, the following operational procedures were observed:

(1) Prior to the start of activities, all communication receivers and transponders were switched OFF to avoid any interference to any other spacecraft while drifting.
(2) With the new orbital elements, critical evaluation of close approach to any other listed spacecrafts was carried out. While crossing nearby spacecrafts, duration of pulsing was limited to minimum, or not done to ensure mutual safety.
(3) As part of final passivation, spacecraft Ni-Cd batteries were disconnected from Main Busses and the charge arrays from solar panels were also disconnected. Self-discharge is expected to finally deplete the batteries of the stored energy.
(4) At the end of operations, all the unused thermal loads were also switched OFF, which were earlier kept ON for thermal balance.
(5) All the propulsion valves were kept closed and it was also ensured that the system was empty.
(6) The telemetry transmitters were switched OFF so that there was no RF emission from the spacecraft.

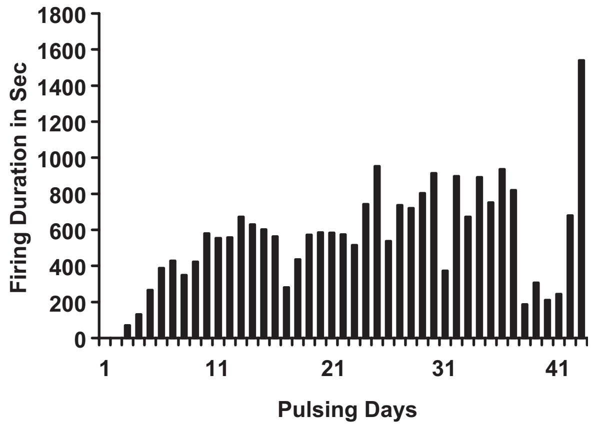

Fig. 2. Firing pulse durations for INSAT-2C relocation.

The maneuver operations were started on June 10, 2003. The maneuvers were continued for nearly 44 days to achieve a drift rate of 1.71°/day. The details of the pulsing duration and orbit achieved each day are illustrated in the Figs. 2 and 3, respectively. On average, thrusters were fired daily for 600 s with a number of pulses of 130 ms duration.

INSAT-2C was successfully decommissioned after its useful mission life on July 30, 2003. Though the target perigee height of 281 km above GSO could not be achieved due to propulsion and visibility constraints, the achieved apogee height of 150 km and perigee height of 127 km above GSO were commensurate with the system constraints. Maximum efforts were taken so that interference to other satellites was avoided during the 44 days of operation. The spacecraft was also passivated at the final stage.

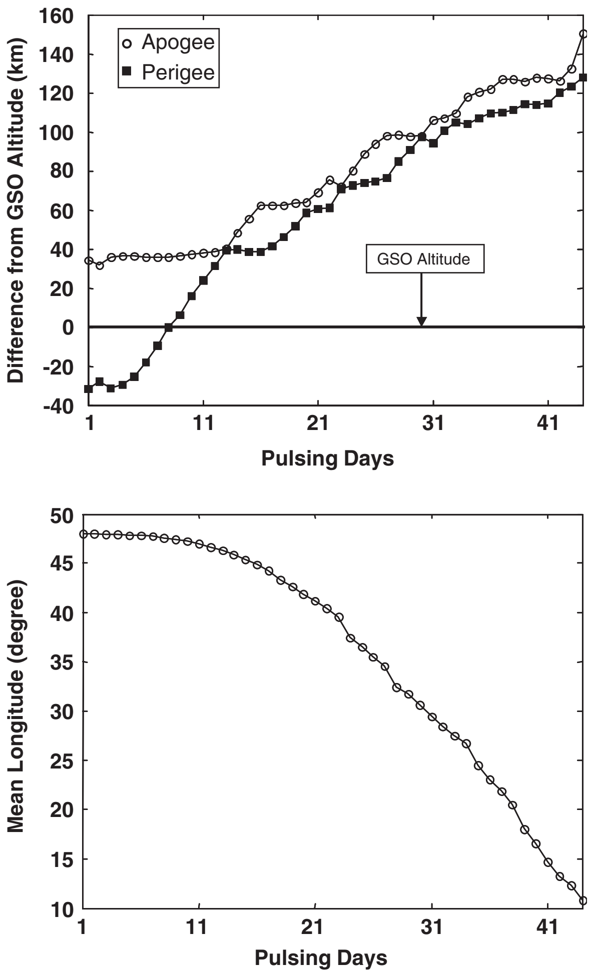

Fig. 3. Changes in INSAT-2C position during relocation operation.

5. Space debris proximity analysis for collision avoidance

There is a need to protect a launch vehicle in its ascent phase, as well as the spacecraft upon injection from any risk owing to debris collision, even though such risk is small. One of the methodologies developed is that of SPAce DEbris PROximity (SPADEPRO) analysis, which is required for COLlision Avoidance or COLA studies. SPADEPRO refers to assessment of collision risk between catalogued resident space objects and a launch vehicle or satellite of interest. The detection of close approaches to satellites/launch vehicles during the launch and early post-deployment phase of their lifetimes is an important subset of the overall problem. Potential collisions during this period can usually be avoided by adjusting the time of launch within a specified launch window.

The basic philosophy of the Space Debris Proximity Analysis hinges on three facets, namely,

(a) computation of collision probability between spacecraft of interest and other resident space objects,
(b) assessment of acceptable collision probability,
(c) choice of appropriate interval for space debris proximity analysis.

For the computation of the collision probability between a spacecraft of interest and other resident space objects, necessary inputs are:

(a) threshold for minimum conjunction distance,
(b) combined trajectory dispersion,
(c) effective collision radius.

The minimum conjunction distance between the spacecraft of interest and other resident space objects within a specified time span is computed in a deterministic sense. This is computationally expensive since trajectories of all the catalogued objects need to be checked vis-à-vis that of the spacecraft of interest. So before this process can proceed, in order to avoid unnecessary computational burden and produce a fast assessment, four filters can be used: an orbital separation filter, an apogee–perigee filter, a time filter, and an epoch filter. The application of the filters drastically reduced the number of catalogued objects to be considered in the proximity analysis. The combined trajectory dispersion for the spacecraft of interest and a particular catalogued object is to be determined for carrying out the space debris proximity analysis. For the spacecraft of interest, trajectory dispersions are obtained through Monte Carlo analysis and for a particular catalogued object, approximate trajectory dispersion values can be fixed by considering the age of the orbital information of the object and the type of orbit it represents. The procedural details are given in [2].

A typical result of the SPADEPRO analysis will be given in terms of identification of time intervals during which the risks of collision with debris is above an acceptable level. The launch of the spacecraft can be postponed by a few minutes to avoid these high-risk intervals. Such a methodology has been successfully implemented during the satellite launches of the Indian Space Research Organization, for example the PSLV-C4 launch was postponed by a few minutes on 12th September 2002. Interestingly, one of the debris pieces that led to this brief postponement is a fragment of PSLV-C3 rocket body.

6. Minimization of GTO lifetime

Many spent upper stages are separated and left in the GTO, which is a highly eccentric orbit with the perigee normally at low altitudes (180–800 km) and the apogee near the geostationary altitude of around 36,000 km. The evolution of objects in GTOs is determined by a complex interplay of atmospheric drag and luni-solar gravity. These orbits are characterized by periodic changes in perigee altitudes caused by gravitational perturbations of the Sun and the Moon. The initial orientation of the orbit just after the launch with respect to the Sun and the Moon predominantly determines the subsequent histories of the orbital evolution. The launch time plays an important role. The combined influence of the luni-solar perturbations and drag can result in lifetime variations from a few months to several decades. The desired effect from the space debris point of view is a short lifetime. Unfortunately, one cannot always use this natural phenomenon to limit the orbital lifetime, as the launch time of a geostationary satellite is dictated by many other factors like thermal aspects and eclipse time related to the spacecraft design. However, through appropriate choice of the initial perigee altitude and launch time, the lifetime in GTO can be significantly reduced. This feature was demonstrated both in the case of GSLV-D1 upper stage as well as that of GSLV-D2.

The predicted history for the orbital evolution of the GSLV-D1 spent third stage is presented in Fig. 4. The uncertainties in the drag-related parameters are taken into consideration in generating a dispersion band on the time for decay. The apogee and perigee histories for orbiting third stage of GSLV-D1 have been obtained using monthly averages of actual solar activity index $F_{10.7}$ from April 2001.

In this study, using the NPOE software with numerical integration of the GTOs, the Earth's gravitational potential up to $J_{6,6}$, luni-solar point mass gravitation with Sun and Moon positions computed from JPL DE405 ephemeris and MSIS90 atmospheric model are used. Here one interesting point is to note a cross-over point in apogee profile occurring around 530 days of the orbital life. In the case of lower drag, the decay occurs owing to sharper decrease in perigee altitude after 530 days due to sharper decrease in perigee from the influence of luni-solar gravity. It can be seen that for the curves with higher drag the lifetimes are longer. Because of higher drag the apogee altitude decreases faster which results in attenuation of luni-solar gravity effects. In cases with higher drag the perigee remains at a relatively higher level as compared to those of cases with lower drag.

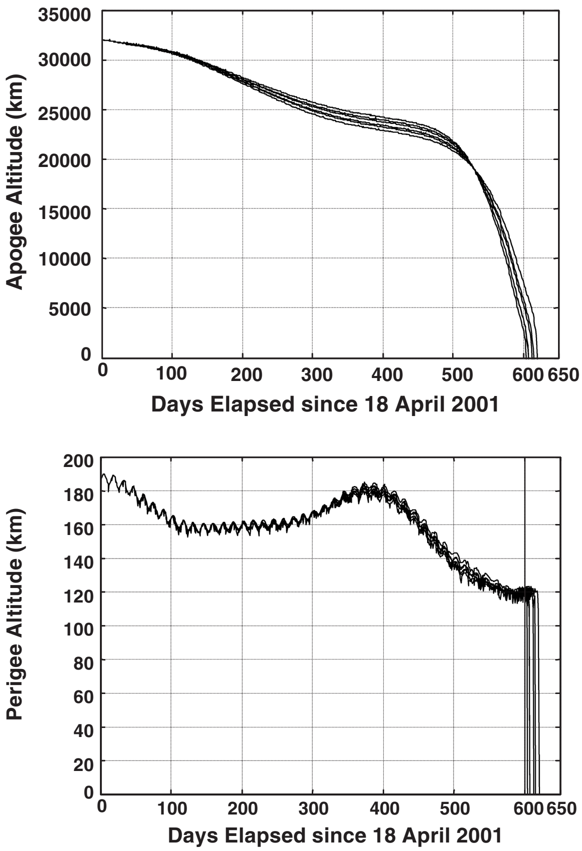

Fig. 4. Orbital evolution of GSLV-D1 rocket body.

During this period, following the cross-over point, the perigee altitude then continues to fall marginally. The evolution of the spent upper stage of GSLV-D1 was studied and it was predicted that the reentry is expected to take place around December 2002/January 2003 [11]. The actual decay took place on January 18, 2003.

7. Conclusion

In this paper, significant developments in ISRO in implementing space debris mitigation measures are briefly described. ISRO considers space debris as an important subject for all the countries. The Debris Mitigation Guidelines brought out by the Inter Agency Space Debris Coordination Committee is a very significant milestone in this respect. In the design and operational phases of the launch vehicle and spacecraft programmes of ISRO, these guidelines are followed to the maximum extent possible consistent with national service requirement. There are still many more issues and many more challenges that space faring nations have to address in

containing the detrimental effects of space debris. ISRO will continue to keep these factors in mind in all its future space endeavors.

Acknowledgements

The authors gratefully acknowledge the contributions of A.K. Anilkumar, P. Bandyopadhyay, V. Ganesan, V. Krishnamurthy, Madan Lal, S. Nirmala, S. Parameswaran, C.G. Patil, M.Y.S. Prasad, R.K. Sharma and P.V. Subba Rao in preparation of this document. The authors express their gratitude to N. Vedachalam, G. Madhavan Nair and K. Kasturirangan for their constant encouragement and support in course of this activity.

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